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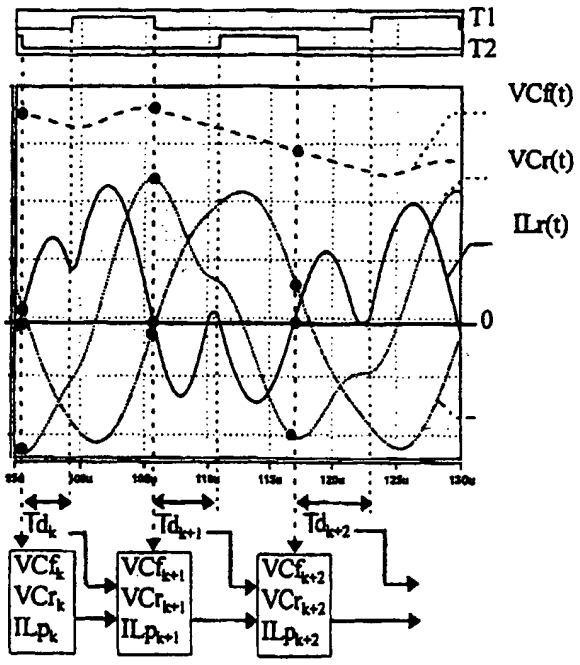
(54) Device and method for electrical regulation with optimal control

(57) Method for regulating a converter having transistors, in which the value of a number N_1 of state variables (V_{cf}, V_{cr}, I_{Lp}) is measured and stored, then action is carried out on a number N_2 of control variables (T_{dk}, T_{dk+1}, T_{dk+2}). N_1 being greater than N_2, the value of the control variables is calculated, at a given instant, for a number P of periods such that the product of N_2 multiplied by P is greater than or equal to N_1.

FIG.4



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Description

[0001] The present invention relates to the field of DC/AC conversion of electrical energy.

[0002] Inverters are supplied with a DC voltage and deliver as output an AC voltage by virtue of one or more transistor half-bridges. The output AC voltage is generally subjected to filtering.

[0003] Inverters of this type are, amongst other things, used for the electrical power supply of an X-ray tube.

[0004] An X-ray tube mounted, for example, in a medical radiology instrument, comprises a cathode and an anode which are both enclosed in an evacuated leaktight casing, so as to produce electrical insulation between these two electrodes. The cathode produces an electron beam which is received by the anode on a small surface constituting a focus from which the X-rays are emitted. -

[0005] When a high supply voltage is applied using a generator to the terminals of the cathode and the anode, so that the cathode is at a negative potential -V and the anode is at a positive potential +V, with respect to the potential of the cathode, a so-called anodic current is set up in the circuit through the generator which produces the high supply voltage. The anodic current passes through the space between the cathode and the anode in the form of an electron beam which bombards the focus.

[0006] The anode is in the shape of a flat disc which is supported by a shaft, driven in rotation by a rotor of an electric motor, the stator of which is arranged outside the casing, with the aim of promoting the dissipation of the energy. The X-ray tube is arranged in an enclosure filled with an insulating refrigerant.

[0007] The characteristics of the X-rays which are emitted by the tube, in particular their hardness, depend on a number of parameters, including the value of the high voltage applied to the electrodes. This high voltage should be adjustable in order to obtain the desired characteristics, and should remain constant throughout the radiological exposure time, so as not to alter the operating characteristics of an X-ray receiver which receives the X-rays which have passed through the object which is undergoing examination.

[0008] X-rays tubes for medical diagnosis operate in pulses. It is therefore important for the time taken to establish the high voltage, as well as the time taken to return from this high voltage to a zero value, to be as short as possible.

[0009] A high-voltage generator for an X-ray tube generally comprises a supply circuit which delivers a DC voltage E starting with an AC voltage delivered by the mains. The voltage E is applied to the terminals of an inverter of the type which comprises at least one transistor half-bridge, each branch of the half-bridge comprising a switch S consisting of a transistor T and a freewheeling diode D mounted in antiparallel. The AC signal delivered by the inverter is applied, via a filter, to the primary of a step-up voltage transformer having a turns ratio k. The secondary of the step-up voltage transformer is connected to a rectifying and filtering circuit comprising at least one diode halfbridge and capacitors C_f for filtering the voltage.

[0010] In known fashion, the inverter comprises a transistor pair connected in series to the output terminals of the supply circuit. A diode is connected between the collector and the emitter of each transistor T, so that its anode is connected to the emitter of the corresponding transistor. The bases of the transistors are connected to a control circuit which delivers switching signals for the transistors. In the case of a single half-bridge, the two output terminals of the inverter consist of the common point of the two branches of the half-bridge and of a point common to two capacitors of the half-bridge which are mounted in parallel and, in the case of two half-bridges, of each point common to the two transistors of a half-bridge.

[0011] The output filter of the inverter comprises, for example, a coil L_r and a capacitor C_r which are arranged in series, and a coil L_p which is arranged in parallel with the capacitor C_r. One of the terminals of the filter is connected to an output terminal of the inverter, and the other terminal is connected to a terminal of the primary circuit of the transformer. A filter with single resonance may also be used.

[0012] The rectifying circuit connected to the secondary of the step-up voltage transformer consists, for example, of a two-diode bridge, the point common to the two diodes being connected to one of the output terminals of the secondary of the transformer, two capacitors C_{f1} and C_{f2} being arranged in parallel with the diode bridge, the other terminal of the secondary of the transformer being connected to the point common to the two capacitors C_f.

[0013] The control circuit essentially comprises a comparator, a circuit for measuring the current I_{1r}, at the primary of the transformer, and a circuit for developing the switching signals for the transistors of the inverter. One of the two output terminals of the comparator is connected to the common point of two resistors of a voltage divider, to which the DC supply voltage V_{cf} of the X-ray tube is applied, and the other is connected to a reference voltage source. The output terminal of the comparator delivers a signal whose amplitude is proportional to the difference between the two voltages applied to the input terminals, and it is connected to an input terminal of the circuit for developing the switching signals, so as to bring about a change in the frequency of the control signals for the transistors. The output terminal of the circuit for measuring the current in the primary of the transformer is connected to another input terminal of the circuit for developing the switching signals, with the aim of detecting and avoiding certain malfunctions of the inverter.

[0014] In conventional fashion, the control variable on which the control circuit acts is the time period T_d until the transistors are turned on, starting from the instant when the current of the inverter reaches a zero value.

[0015] The presence of a filter with double resonance makes it possible to have the current of the inverter change as a monotonically increasing function of frequency, between the parallel resonant frequency and the series resonant frequency, the values of which depend on the values of the capacitor C_r of the series coil L_r and of the parallel coil L_p of the filter. It therefore seems possible to control the power transmitted to the X-ray tube by the operating frequency of the inverter, and consequently the activation delay T_d. A filter with single resonance also makes it possible to control the power by the activation delay T_d.

[0016] However, known control circuits do not make it possible to set the DC supply voltage V_{cf} of the X-ray tube to its desired value until too much time has elapsed, which results in time being wasted and by a dose of X-rays being received superfluously by the patient. This is because the efficiency of the X-rays for taking exposures is proportional to the voltage V_{cf} raised to the fifth power. The dose of X-rays received before the desired voltage V_{cf} is established, cannot be used for taking exposures.

[0017] These control circuits leave some degree of ripple in the voltage V_{cf} after it has been established. This ripple is at a frequency of 100 or 300 Hz, depending on the supply type used: single-phase or three-phase. These ripples are even more problematic since the number of exposures taken per second may be as many as thirty and since it leads to an instability in the images. For a scanner, which is provided with a rotary source so as to obtain three-dimensional information, the image computation presupposes that the images are stable and consequently that the voltage is constant.

[0018] It is therefore desirable to overcome the drawbacks mentioned above, by providing a method and a device for regulation which make it possible to reduce the time taken to establish the voltage V_{cf} at the start of an exposure.

[0019] It is further desirable to reduce the ripple in the voltage V_{cf} in steady state.

[0020] The method for regulating a converter having transistors, in an embodiment of the invention, comprises steps of measuring and storing the value of a number N_1 of state variables, then of acting on a number N_2 of control variables. V_{cf} being greater than N_2, the value of the control variables is calculated, at a given instant, for a number P of periods such that the product of N_2 multiplied by P is greater than or equal to N_1 It is thus possible to act on all the state variables while retaining the possibility of establishing a hierarchy between them and of assigning priority to one or other of them.

[0021] In one embodiment of the invention, there is a single control variable, which is a time variable. In this case, a number P of periods equal to the number N_1 of state variables will generally be chosen, which leads to a system of N_1 equations with P unknowns, the P unknowns being the values of the time variable for each period.

[0022] In one embodiment of the invention, the regulation is of the proportional-integral type for one of the state variables and of the proportional type for the other state variables.

[0023] Advantageously, the state variables are measured each time one of the said state variables reaches a predetermined threshold value, for example a zero value.

[0024] In one embodiment of the invention, the state variables are the current I_{Lr} in a series filtering inductor, the current I_{Lp} in a parallel filtering inductor, the voltage V_{cr} across the terminals of a filtering capacitor, and the output voltage V_{cf} of the converter.

[0025] The device for regulating an energy conversion assembly, according to the invention, comprises means for discretely measuring the values of a number N_1 of state variables, and means for controlling a number N_2 of control variables, with the aim of obtaining, at the output of the control assembly, an optimum time variation of one or more of the state variables, it being possible for the variation of the energy conversion assembly over a period between two measuring instants to be estimated by knowing the state variables at the first measuring instant and the control variables during the period in question. The device comprises means for developing the values of the N_1 control variables over a number P of measuring instants, N_1 being greater than N_2, with P such that the product of N_2 multiplied by P is greater than or equal to N_1.

[0026] By virtue of the invention, a significant reduction, of the order of 60%, is obtained in the time taken to establish the voltage V_{cf}. A very great reduction is thus obtained in the dose received superfluously by the patient during the set-up time. This also improves the quality of the images obtained with the radiology device, by virtue of better stability of the voltage V_{cf} in steady state.

[0027] Of course, the invention can be applied to various types of converters and makes it possible for their performance to be improved significantly.

[0028] The invention will be understood more clearly, and other advantages will emerge, from the following detailed description of an embodiment, taken by way of entirely non-limiting example and illustrated by the appended drawings, in which:

Figure 1 is a schematic diagram of an energy conversion device;

Figure 2 is a time diagram showing the variation in the current I_{1r} in the series inductor;

Figure 3 shows the change in the status of the transistors and of the diodes of the converter over one half-cycle;

Figure 4 shows the waveforms of the main variables during a transient;

Figures 5 to 7 are time diagrams of the change in the state variables subsequent to a modification of V_{cr}, I_{1p} and T_d; and

Figure 8 is a schematic diagram of the regulating device according to the invention.

[0029] In Figure 1, a DC voltage source E supplies a half-bridge provided with two switches S_1 and S_2. each composed of a power transistor, for example of the insulated-gate bipolar transistor (IGBT) type, and of a freewheeling diode. The inductors L_1 and L_2 serve to assist switching. The capacitors C_1 and C_2 are mounted in series and filter the voltage E. The voltage E is delivered by the mains AC voltage which is rectified by means (not shown).

[0030] The center output of the half-bridge formed by the switches S_1 and S_2 is connected to one terminal of the primary of a transformer T_R, the other terminal being connected to the point common to the two filtering capacitors C_1 and C_2. A filter with double resonance is arranged between the point common to the two switches S_1 and S_2 and the transformer T_R. This filter comprises a series inductor L_r, a series capacitor C_r and a parallel inductor L_p which is mounted in parallel with the capacitor C_r The transformer T_R steps up the voltage by a coefficient K. This voltage is then rectified by a diode half-bridge and by two filtering capacitors C_f. Of course, a four-switch inverter and a four-diode rectifier could be used. The output voltage V_{cf} of the rectifier is sent to an X-ray tube (not shown).

[0031] The value of the components of the filter is chosen so as to define a parallel resonant frequency $F_p = 20$ kHz so as to be outside the audible spectrum, and a series resonant frequency F_S which is greater than the parallel resonant frequency and is chosen in accordance with the frequency limitations imposed by the switching times of the transistors of the half-bridge of the inverter, for example 70 kHz. When the operating frequency, lying between the parallel resonant frequency F_p and the series resonant frequency F_s, approaches the series resonant frequency F_s, the impedance of the filter decreases, which leads to an increase in the current and therefore in the power transmitted to the transformer. Conversely, when the operating frequency decreases and approaches the parallel resonant frequency F_p, the impedance of the filter increases and the output current I_o tends towards a zero value. It is therefore possible to control the current I_{Lr}, by the operating frequency.

[0032] However, the values of the inductors L_r and L_p and of the capacitor C_r of the filter are only known to within 5%. Moreover, the resonant frequencies are determined by the values of these components. Control by means of the frequency is not very effective because of this inaccuracy. A different approach is therefore used, involving the difference between the operating frequency and the actual series resonant frequency. Specifically, when the operating frequency tends towards the series resonant frequency F_s, the conduction delay T_d of the diodes of the switches tends towards zero. The zero crossing of the current I_{Lr}, in the series inductor L_r is detected, and a counter is triggered until the transistor of the opposite branch of the half-bridge is caused to switch on. It is thus possible to synchronize with the zero crossing of the current I_{Lr}.

[0033] In Figures 2 and 3, small positive and negative threshold values of I_{Lr}. are defined, on the basis of which the period T_d after which the transistor is switched on is counted down.

[0034] When the current I_{1r} at the end of a negative half-cycle becomes greater than the negative threshold value, the counting of the period T_d is triggered. At the end of the period T_d the current I_{Lr} has become positive and the switching-on of the transistor T_1 is triggered. Then, when the current I_{Lr} becomes less than the positive threshold, the counting of the period T_d is again triggered. When the current I_{Lr} becomes negative, the diode D_1 becomes forward-biased. When the period T_d has elapsed, the transistor T_2 is switched on.

[0035] As illustrated in Figure 4, the sampling instants are chosen such that the current I_{Lr} is zero, and at this instant the value of the other state variables V_{cf}, V_{cr} and I_{Lp} are measured, V_{cr} being the voltage across the terminals of the series capacitor C_r, and I_{LP} being the current in the parallel inductor L_p These values are then stored in a memory. In view of the characteristics of the system, the waveform of the state variables between two sampling instants depends only on the value of the three aforementioned state variables V_{ct}, V_{cr}, I_{Lp} and on the value of the chosen activation delay T_d. On the basis of these data, it is possible to try to find the transfer function and carry out simulations over a half-cycle while remaining close to steady state.

[0036] The aim of the regulation of a converter for an X-ray tube is to obtain the output voltage V_{cf} while maintaining correct operation of the converter. However, acting on the single control variable consisting of the activation delay T_d over one half-cycle, only makes it possible to regulate one of the state variables, namely V_{cf}, which runs the risk of leading to undesired values of the voltage V_{cr} and the current I_{Lp}.

[0037] Regulation is therefore carried out over three half-cycles, and there are thus three available control variables T_{dk}, T_{dk+1}, T_{dk+2}, which makes it possible to provide as many control variables as there are state variables and to reach a stable state at the end of the third half-cycle. Since regulating the voltage V_{cf} takes priority over regulating the voltage

V_{cr} and the current I_{Lp}, provision is made to add an integral term to the regulation of V_{cf}, while the regulation of V_{cr} and I_{Lp} is merely proportional.

[0038] In other words, in order to regulate suitably a system having a number of state variables greater than the number of control variables, this regulation is carried out over a number of half-cycles greater than 1, so that the product of the number of half-cycles multiplied by the number of control variables is greater than the number of state variables, in order to have a number of transfer equations equal to this product and therefore greater than the number of state variables. It is therefore possible to predict the future status of the regulating system with equations of the type $X(k+1) = A^*X(k) + B^*T_d$, in which X is the vector formed by the state variables. The values of the matrices A and B are determined close to a particular operating point in steady state.

[0039] These constants may be calculated by simulating low-amplitude transients with respect to this operating point, V_{cf} and T_d being fixed. Simulations are successfully carried out on the voltage V_{cr} (Figure 5) starting from the following initial conditions: $V_{crk} = V_{crs} + dV_{cr}$, $I_{Lpk} = I_{Lps}$ and $V_{cfk} = V_{cfs}$, the values assigned an index S corresponding to the operating point in steady state. The same simulation is carried out on the current I_{Lp}, starting from the following initial conditions: $V_{crk} = V_{crs}$, $I_{Lpk} = I_{Lps}$ and $V_{cfk} = V_{cfs}$. The curves represented in Figure 6 are obtained. A last simulation is carried out while keeping the state variables to their value of the operating point in steady state, and by modifying the value of the activation delay: $T_{dk} = T_{ds} + dT_d$.

[0040] By virtue of this simulation, the transfer function of the converter close to a stable state is obtained, this being written as follows:

$$\begin{pmatrix} VCr_{k+1} - VCrs \\ ILp_{k+1} - ILps \\ VCf_{k+1} - VCfs \end{pmatrix} = \begin{pmatrix} \frac{\partial VCr_{k+1}}{\partial VCr_k} & \frac{\partial VCr_{k+1}}{\partial ILp_k} & 0 \\ \frac{\partial ILp_{k+1}}{\partial VCr_k} & \frac{\partial IL_{k+1}}{\partial ILp_k} & 0 \\ \frac{\partial VCf_{k+1}}{\partial VCr_k} & \frac{VCf_{k+1}}{\partial ILp_k} & 1 \end{pmatrix} \bullet \begin{pmatrix} VCr_k - VCrs \\ ILp_k - ILps \\ VCf_k - VCfs \end{pmatrix} + \begin{pmatrix} \frac{\partial VCr_{k+1}}{\partial td_k} \\ \frac{\partial ILp_{k+1}}{\partial td_k} \\ \frac{\partial VCf_{k+1}}{\partial td_k} \end{pmatrix} \bullet \left(td_k - tds \right)$$

[0041] The value of the activation delay for a given half-cycle is therefore calculated from the following formula:

$$\left(td_k - tds \right) = \begin{pmatrix} k_{vcr} & k_{ILp} & k_{vcf} \end{pmatrix} \bullet \begin{pmatrix} VCrs - VCr_k \\ ILps - ILp_k \\ VCfs - VCf_k \end{pmatrix}$$

in which the dynamic response of the system in closed loop depends on the choice of the gains k_{vcr}, k_{ILp} and k_{vcf}. These gains may be calculated using the Ackermann method, starting with the gains of the transfer function. Tables of values of these gains may be stored in memory for various values of current and voltage, to be extracted later during the operation of the converter, illustrated in Figure 8.

[0042] The values of the three state variables I_{Lp}, V_{cr} and V_{cf} are extracted from the power part 1 of the converter at the sampling instants. These values are relayed, via delay cells, to comparators forming part of a digital processing unit 2. The other input of the comparators is connected to a circuit 3 for developing reference values V_{cfs}, V_{crs} and I_{Lps}.

[0043] The circuit 3 develops the aforementioned reference values on the basis of the voltage V_{cfs} and the desired activation delay T_{ds}. At the output of the comparators, the quantities ΔI_{Lpk}, ΔV_{crk} and ΔV_{cfk} are assigned their respective gain coefficients then added. The quantity ΔV_{ctk}, assigned a gain coefficient k_1, is delivered to an integrator circuit in order to provide the regulation with an integral term and ensure the priority afforded to the regulation of the V_{cf} The output of the said integrator circuit is also connected to the circuit which adds the other quantities. The output of the adder circuit is connected to another adder circuit which receives the value of T_d. from the circuit 3. The activation delay T_{dk+1} for the next half-cycle is obtained at the output of this other adder circuit and is delivered to a circuit (not shown) for controlling the transistors of the power part 1.

[0044] By virtue of the invention, the regulation of the converter is improved considerably while reducing the rise time of the output voltage and the ripple in steady state. Depending on the gain coefficients which are chosen, it is, for example, possible to allow for an exponential growth in the voltage at the start of a voltage rise ramp, in order to profit

from a high current at low voltage, which, in the case of an X-ray tube, makes it possible to reduce the doses received by the patient, and also at the end of a voltage rise ramp in order to avoid excessive ripples in the current. Of course, the invention can be applied to extremely wide-spread types of converters intended for supplying different kinds of electrical loads.

Claims

1. A method for regulating a converter having transistors, in which the value of a number N_1 of state variables is measured and stored, then action is carried out on a number N_2 of control variables, wherein, N_1 being greater than N_2, the value of the control variables is calculated, at a given instant, for a number P of periods such that the product of N_2 multiplied by P is greater than or equal to N_1.

2. The method according to claim 1, wherein N_2 is equal to unity and in that the control variable is a time variable.

3. The method according to claim 1 or 2, wherein regulation is of the proportional - integral type for one of the state variables and of the proportional type for the other state variables.

4. The method according to any one of the preceding claims, wherein the state variables are measured each time one of the state variables reaches a predetermined threshold value.

5. The method according to claim 4, wherein the state variables are measured each time one of the state variables reaches a zero value.

6. The method according to any one of the preceding claims, wherein the state variables are the current I_{Lr} in a series filtering inductor, the current I_{Lr} in a parallel filtering inductor, the voltage V_{cr} across the terminals of a filtering capacitor, and the output voltage V_{cf} of the converter.

7. A device for regulating an energy conversion assembly, comprising means for discretely measuring the values of a number N_1 of state variables, and means for controlling a number N_2 of control variables, with the aim of obtaining, at the output of the control assembly, an optimum time variation of one or more of the state variables, it being possible for the variation of the energy conversion assembly over a period between two measuring instants to be estimated by knowing the state variables at the first measuring instant and the control variables during the period in question, comprising means for developing the values of the N_2 control variables over a number P of measuring instants, N_1 being greater than N_2, with P such that the product of N_2 multiplied by P is greater than or equal to N_1.

8. The device according to claim 7, wherein N_2 is equal to unity and in that the control variable is a time variable.

9. The device according to claim 7 or 8, wherein the regulation is of the proportional - integral type for one of the state variables and of the proportional type for the other state variables.

10. The device according to any one of the preceding claims, comprising means for measuring state variables each time one of the state variables reaches a predetermined threshold value.

11. The device according to claim 10, comprising means for measuring state variables each time one of the state variables reaches a zero value.

12. The device according to any one of the preceding claims, wherein the state variables are the current I_{Lr} in a series filtering inductor, the current I_{Lp} in a parallel filtering inductor, the voltage V_{cr} across the terminals of a filtering capacitor, and the output voltage V_{cf} of the converter.

FIG.1

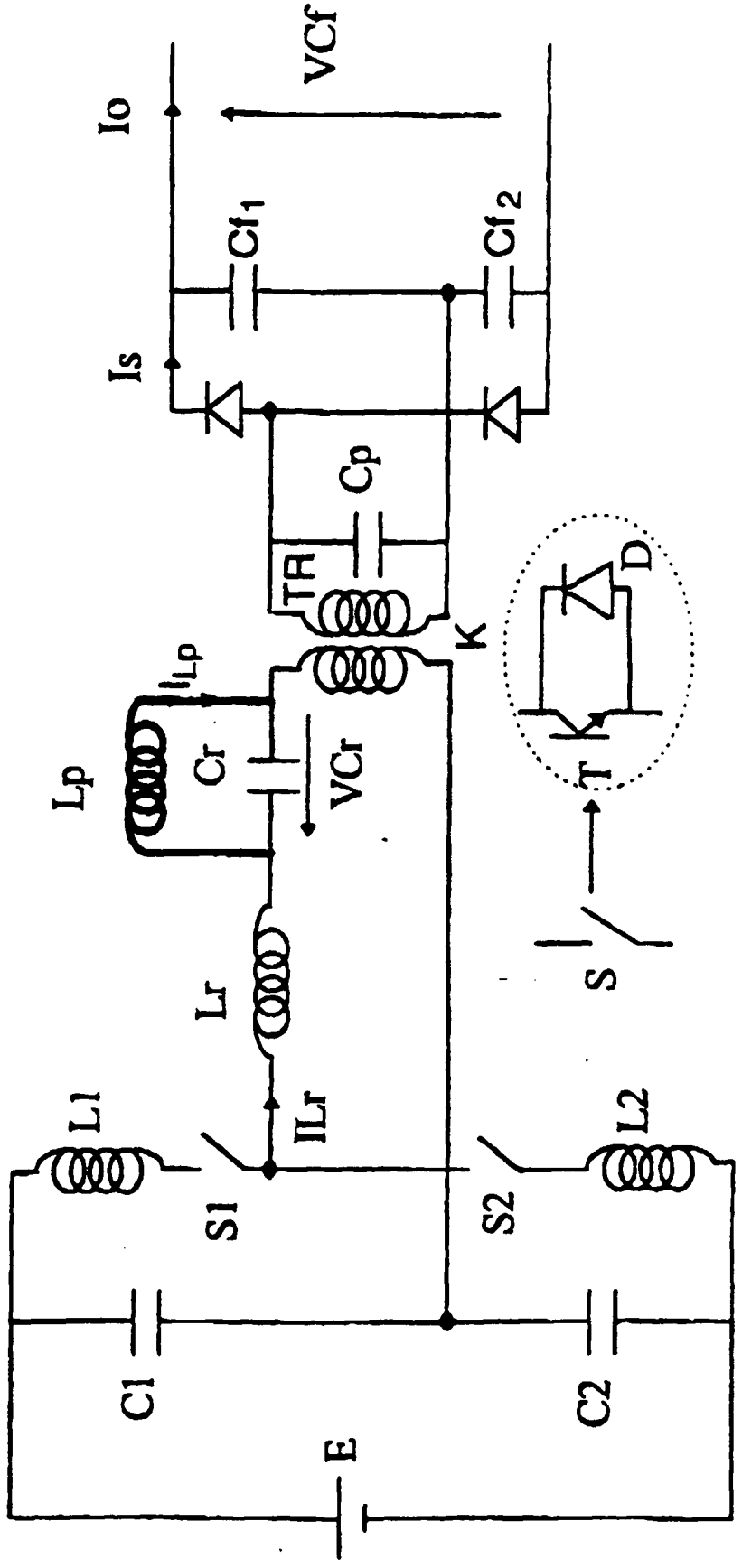
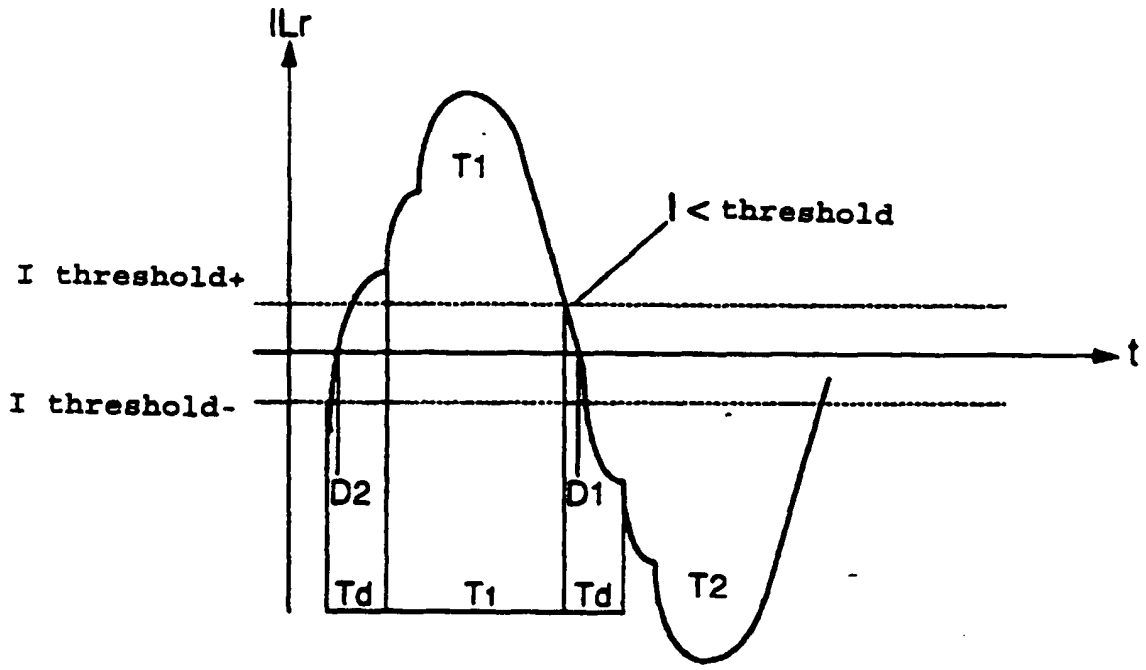


FIG.2



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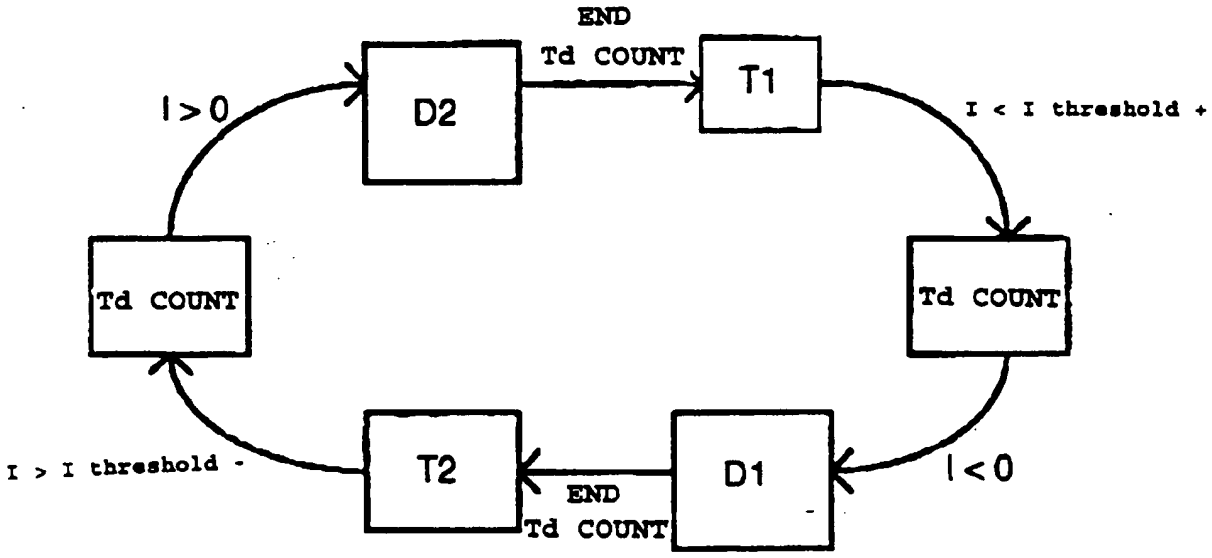
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Td COUNT

FIG.4

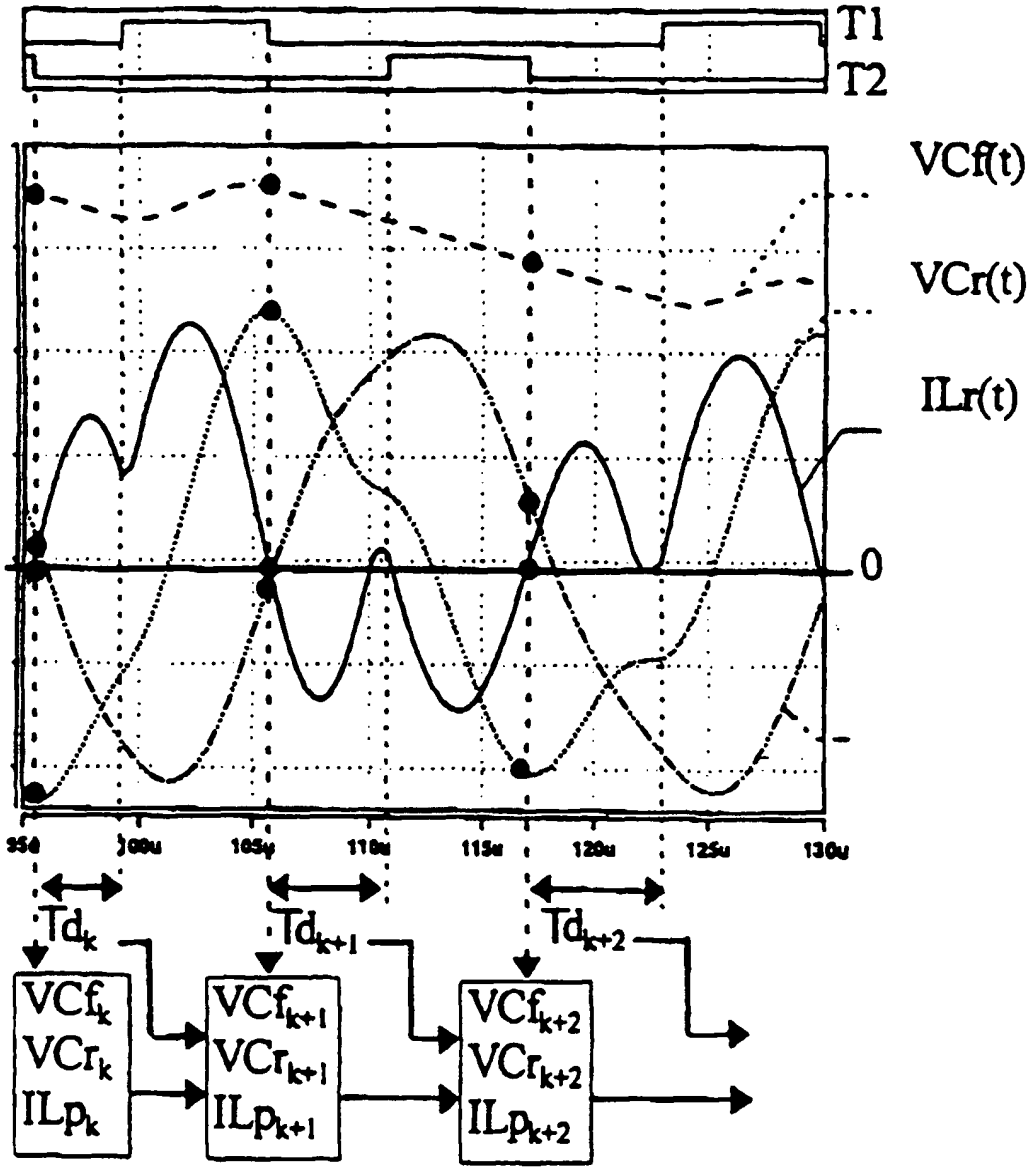
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FIG.5

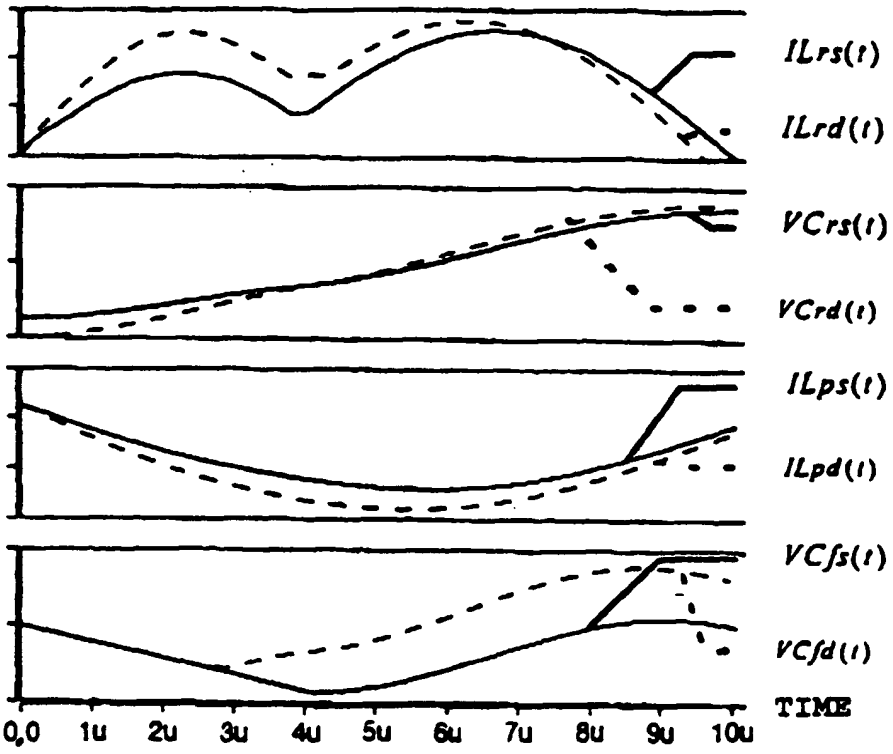
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FIG.6

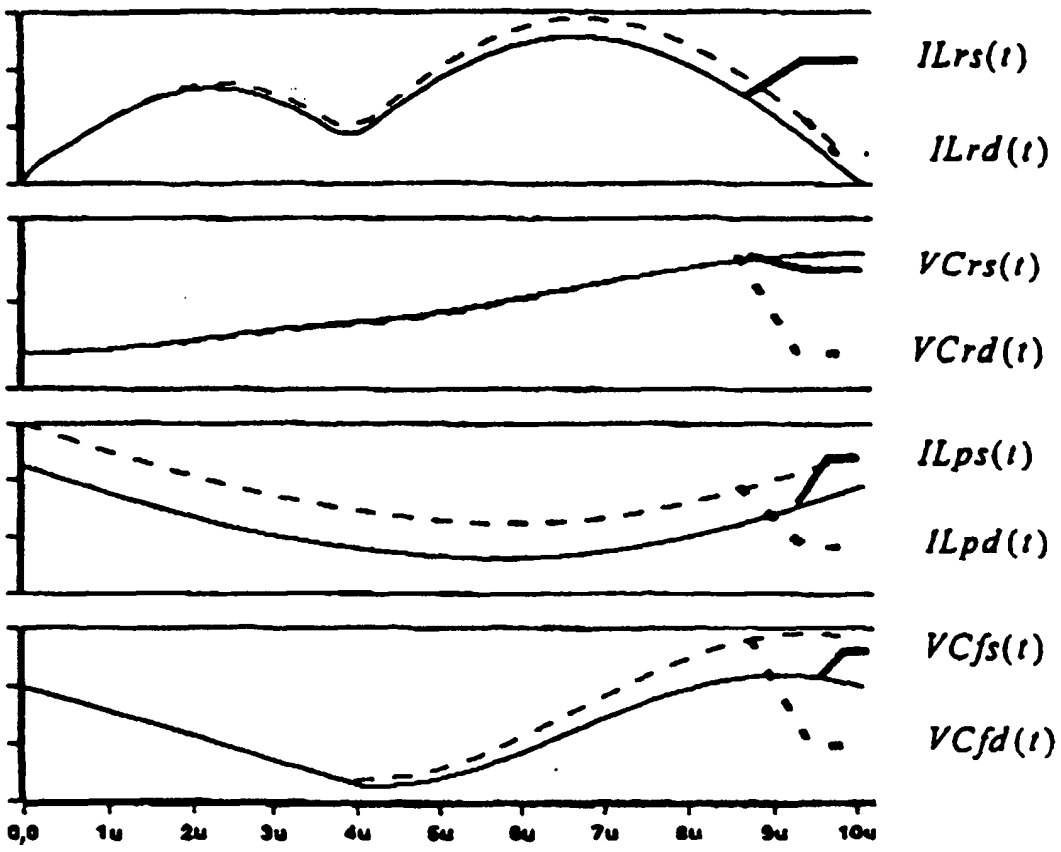
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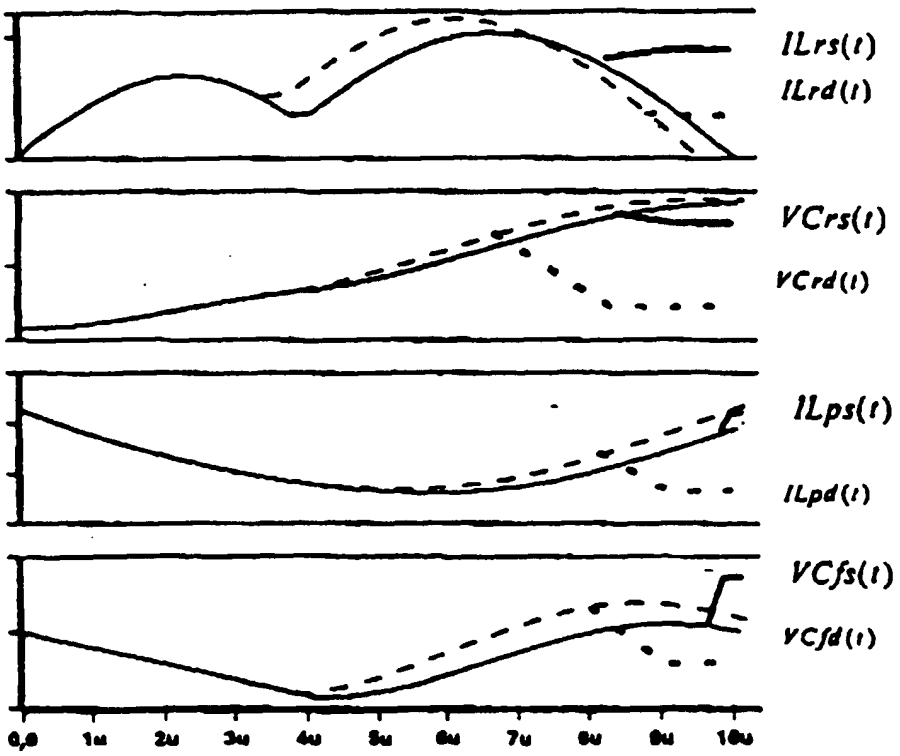
FIG.7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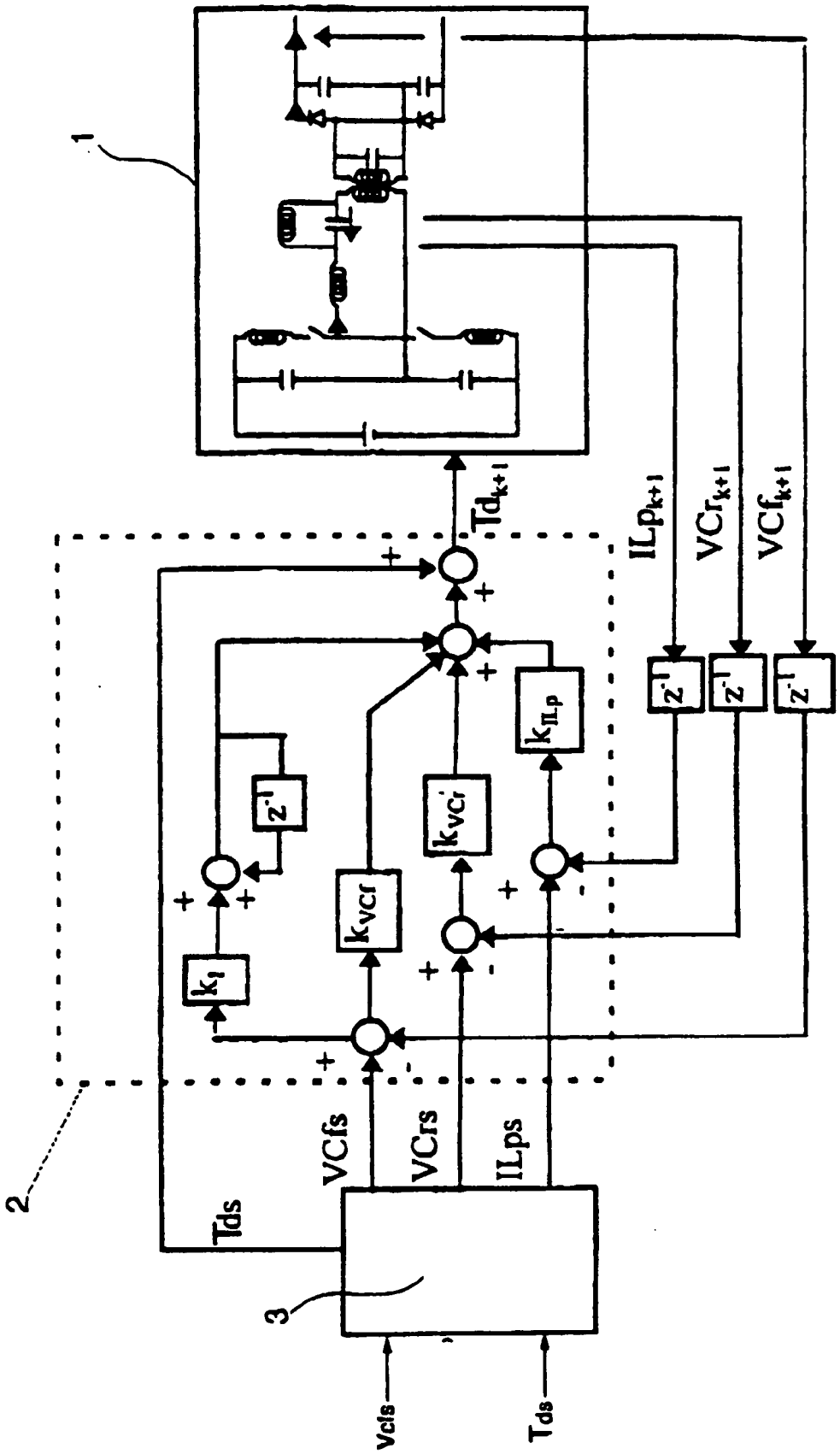
10u

FIG.8


1
2
3
Td$_{k+1}$
ILp$_{k+1}$
VCr$_{k+1}$
VCf$_{k+1}$
Z^{-1}
k$_{ILp}$
k$_{VCr}$
k$_{VCf}$
k$_I$
VCfs
VCrs
ILps
Tds
Vcfs
Tds